

Meson Photoproductions Off Nucleons In The Chiral Quark Model

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Abstract

The meson photoproductions off nucleons in the chiral quark model are described. The role of the S-wave resonances in the second resonance region is discussed, and it is particularly important for the Kaon, η and η' photoproductions.

Meson photoproductions of nucleons have always been a very important field to study the structure of hadrons. It was the early investigations by Copley, Karl and Obryk[1] and Feynman, Kisslinger and Ravndal[2] in the pion photoproduction that provided the first evidence of an underlying $SU(6) \otimes O(3)$ symmetry for the baryon structure in the quark model. Extensive calculations and discussions of the photoproduction of baryon resonances later have not changed the conclusion in Refs. 1 and 2 significantly. These calculations in the framework of the quark models have been limited on the transition amplitudes that are extracted from the photoproduction data by the phenomenological models, thus it is less model independent. The challenge is whether one could go one step further to confront the photoproduction data directly with the quark model. Such a step is by no means trivial, since it requires that the transition amplitudes in the quark model have correct off-shell behavior, which are usually evaluated on shell. More importantly, it also requires that the model with explicit quark and gluon degrees of freedom give a good description of the contributions to the photoproductions from the non-resonant background, which are usually used to evaluate the contributions from s-channel resonances. The low energy theorem in the threshold pion photoproduction[3] is a

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crucial test in this regard, which the non-resonant contributions dominate in the threshold region. Our investigation[4] showed that the simple quark model is no longer sufficient to recover the low energy theorem, and one has to rely on low energy QCD Lagrangian so that the meson baryon interaction is invariant under the chiral transformation. During the past three years, we have extended it to the kaon[5] and η [6] photoproductions by combining the low energy QCD Lagrangian and the quark model, and the initial results showed very good agreements between the theory and experimental data with far less parameters. In the remaining part of this paper, I would like to review the quark model framework for the meson photoproductions, and discuss the important role of s-wave resonances, in particular, those in the second resonance region in the K , η and η' photoproductions.

We shall discuss briefly the chiral quark model approach to the meson photoproductions of the nucleon, as the detailed formalism in the quark model has been given in Refs. 5 and 6. There are four components for the photoproductions of the pseudo-scalar mesons based on the low energy QCD Lagrangian in Ref. 7; the contact term and the s-, u- and t- channel contributions, thus the matrix element for the meson photoproductions can be written as

$$\mathcal{M}_{if} = \mathcal{M}_c + \mathcal{M}_t + \mathcal{M}_s + \mathcal{M}_u. \quad (1)$$

The contact term \mathcal{M}_c in Eq. 4 is generated by the gauge transformations of the axial vector in the QCD Lagrangian. It is proportional to the charge of the outgoing mesons, therefore, it does not contribute to the productions of the charge neutral mesons, such as the K^0 productions in the reactions $\gamma N \rightarrow K\Sigma$. Moreover, the integrations of the spatial wavefunctions of the initial and final baryons generate a form factor that has a maximum value at the forward angle and decreases as the scattering angle between the incoming photon and the outgoing meson increases. This leads to an interesting prediction from the quark model; the charged meson productions should be forward peaked above the threshold because of the dominance of the contact term in the low energy region. The data in charged kaon and the neutral η productions are quite consistent with this conclusion. The second term \mathcal{M}_t in Eq. 1 is the t-channel K^+ exchange, and it is proportional to the charge of the outgoing mesons as well. This term is required so that the total transition amplitude in Eq. 4 is gauge invariant. The other t-channel exchanges, such as the K^* and $K1$ exchanges in the kaon productions, which played an important role in Ref. 8, are excluded with the input of the duality hypothesis[9, 10]. This was not imposed in our early investigation[5] of the kaon photoproductions, in which the K^* exchange was included.

The u-channel contributions \mathcal{M}_u in Eq. 1 include Σ ($\Lambda + \Sigma^0$) exchanges for the $\Sigma^\pm(\Sigma^0)$ final states, the Σ^* exchanges and the excited hyperon exchanges, of which the formulae have been given in Ref. 5. The excited hyperons in this framework are treated as degenerate so that their total contributions can be written in a compact form in the quark model. This is a good approximation since the contributions from the u-channels resonances are not sensitive to their precise mass positions. The transition amplitude \mathcal{M}_s

in Eq. 1 is

$$\mathcal{M}_s = \sum_R \frac{2M_R}{s - M_R(M_R - i\Gamma_R(\mathbf{q}))} e^{-\frac{\mathbf{k}^2 + \mathbf{q}^2}{6\alpha^2}} \mathcal{O}_R, \quad (2)$$

where the resonance R has the mass M_R and total width Γ_R , \mathbf{k} and \mathbf{q} are the momenta of incoming photons and outgoing mesons, and \sqrt{s} is the total energy of the system. The operator \mathcal{O}_R in Eq. 3 depends on the structure of resonances, and it is divided into two parts: the s-channel resonances below 2 GeV and those above 2 GeV that could be regarded as continuum contributions. The electromagnetic transitions of the s-channel baryon resonances and their meson decays have been investigated extensively in the quark model[1, 11, 12, 13] in terms of the helicity and the meson decay amplitudes. These transition amplitudes for s-channel resonances below 2 GeV have been translated into the standard CGLN[3] amplitudes in Refs. 5 and 6 for the proton target and 14 for the neutron target in the harmonic oscillator basis. The advantage of the standard CGLN variables is that the kinematics of the meson photoproductions has been thoroughly investigated[15], the various observables of the meson photoproductions could be easily evaluated in terms of these amplitudes. Those resonances above 2 GeV are treated as degenerate, since few experimental information is available on those resonances. Qualitatively, we find that the resonances with higher partial waves have the largest contributions as the energy increases. Thus, we write the total contributions from the resonances belonging to the same harmonic oscillator shell in a compact form, and the mass and total width of the high spin states, such as $G_{17}(2190)$ for $n = 3$ harmonic oscillator shell, are used.

If we assume that the relative strength and phases of each term in s-, u- and t-channels are determined by the quark model wavefunction with exact $SU(6) \otimes O(3)$ symmetry, and the masses and decay widths of the s-channel baryon resonances are obtained from the recent particle data group[16], there are four parameters in this calculation; the coupling constant $g_{KN\Sigma}$ or $g_{\eta NN}$, the constituent quark masses m_q for up or down quarks and the strange quarks, and the parameter α^2 from the harmonic oscillator wavefunctions in the quark model. The quark masses m_q and the parameter α^2 are well determined in the quark model, they are

$$\begin{aligned} m_u = m_d &= 0.34 && \text{GeV} \\ m_s &= 0.55 && \text{GeV} \\ \alpha^2 &= 0.16 && \text{GeV}^2. \end{aligned} \quad (3)$$

This leaves only **one** free parameter, the coupling constant α_{KYN} or $\alpha_{\eta NN}$, to be determined in the calculation. The one parameter evaluation[17] for all four isospin channels of the reaction $\gamma N \rightarrow K\Sigma$ shows an excellent overall agreement with the few available data in both differential and total cross sections. It represents a dramatic improvement over the similar calculations in the isobar model[18]. Our investigation in the η photoproductions[6] also showed that the one parameter evaluation has produced very good agreement with the experimental data well beyond the threshold region.

An important feature in the chiral quark model approach is that it relates the photoproduction data directly to the spin flavor structure of the s-channel resonances. This is particularly the case for the S-wave resonances in the second resonance region, $S_{11}(1535)$ and $S_{11}(1650)$. The recent data[19] for the η photoproduction in the threshold region from MAMI provides us more systematic information near the threshold region with much better energy and angular resolution. Thus, it enables us to determine the properties of the $S_{11}(1535)$ resonance more precisely. One property of the $S_{11}(1535)$ resonance, determined from the η photoproduction, is given by the quantity ξ ,

$$\xi = \sqrt{\frac{M_N k \chi_{\eta N}}{q M_R \Gamma_T}} A_{\frac{1}{2}} \quad (4)$$

where M_N (M_R) denotes the mass of the nucleon (resonance), k and q correspond to the momenta of the incoming photon and the outgoing meson η , $\chi_{\eta N}$ is the branching ratio of the resonance to the ηN channel, and Γ_T and $A_{\frac{1}{2}}$ are the total width and the helicity amplitude for the resonance. A study[20] by the RPI group shows that this quantity obtained from the experimental data is model independent, and thus should be calculated in theoretical investigations. This quantity is given by an analytical form in the quark model,

$$\xi = \sqrt{\frac{\alpha_\eta \alpha_e \pi (E^f + M_N)}{M_R^3} \frac{C_{S_{11}(1535)} k}{6 \Gamma_T} \left[\frac{2 \omega_\eta}{m_q} - \frac{2 q^2}{3 \alpha^2} \left(\frac{\omega_\eta}{E^f + M_N} + 1 \right) \right]} \left(1 + \frac{k}{2 m_q} \right) e^{-\frac{q^2 + k^2}{6 \alpha^2}}, \quad (5)$$

where ω_η and E^f are the energies of the outgoing η meson and the nucleon. The coupling of the $S_{11}(1535)$ to ηN in Eq. 5 is determined by the ηNN coupling constant α_η . This provides a consistency condition that must be checked in any microscopic model of baryon decay amplitudes, otherwise, the overall agreement with data from meson photoproduction would be lost. The coefficient $C_{S_{11}(1535)}$ is equal to unity in the naive $SU(6) \otimes O(3)$ quark model. Thus the quantity $C_{S_{11}(1535)} - 1$ measures a deviation of the resonance wavefunction from the underlying $SU(6) \otimes O(3)$ symmetry. Both the $S_{11}(1535)$ and $S_{11}(1650)$ resonances show a strong configuration mixing in more sophisticated models[21].

By treating the coupling constant α_η , the coefficient $C_{S_{11}(1535)}$ and the total decay width Γ_T as free parameters and fitting them to the experimental data, we find[6]

$$\begin{aligned} \Gamma_T &= 198 \text{ MeV} \\ C_{S_{11}(1535)} &= 1.608 \\ \alpha_\eta &= 0.435, \end{aligned} \quad (6)$$

which gives an excellent fit to the recent MAMI data[19]. The above results give

$$\xi = 0.220 \text{ GeV}^{-1}. \quad (7)$$

This value is in good agreement with results of the RPI group[20], which used an effective Lagrangian approach to fit both old data sets and new data from the Mainz group. An extraction of the helicity amplitude $A_{1/2}^p$ from the quantity ξ depends on the ηN branching ratio $\chi_{\eta N}$, which is not precisely known at present. One could use, as a guide, the result from a recent coupled channel analysis by Batinić *et al*[22]. There the branching ratios to ηN and πN channels

$$\chi_{\eta N} = 0.63 \text{ and } \chi_{\pi N} = 0.31, \quad (8)$$

were found for the $S_{11}(1535)$ resonance, the latter being in good agreement with a result from the VPI group[23]. These lead to the helicity amplitude

$$A_{1/2}^p = 98.9 \cdot 10^{-3} \text{ GeV}^{-1/2}. \quad (9)$$

However, the total width Γ_T for the resonance $S_{11}(1535)$ varies significantly when extracted from recent partial wave analyses[23, 22] and the η photoproduction data[19]. Thus, the helicity amplitude $A_{1/2}^p$ could not be determined reliably at present.

The constant $C_{S_{11}(1535)} = 1.606$ in Eq. 6 signals a large deviation mixing from the $SU(6) \otimes O(3)$ symmetry for the resonance $S_{11}(1535)$, and it is unlikely that the configuration mixing effects would account for such a large discrepancy. This problem has been known for some time in the quark model. The helicity amplitude $A_{1/2}^p$ from quark model calculations has[13, 12] remained near $150 \cdot 10^{-3} \text{ GeV}^{-1/2}$, while the branching ratio for the $S_{11}(1535)$ resonance decaying to ηN is too small[6, 12]. It has been suggested[24] that a quasi-bound $K\Sigma$ state with properties remarkably similar to the resonance $S_{11}(1535)$ may be responsible for the large ηN branching ratio. Such a scenario is unlikely since the data[25] for the electromagnetic transitions, in particular the Q^2 dependence of the helicity amplitude $A_{1/2}^p$, indicate that the resonance $S_{11}(1535)$ should be dominantly a q^3 state at higher Q^2 according to the pQCD counting rule[26]. In Ref. 27, we show that there is a considerable experimental evidence for a third S_{11} resonance with mass 1.712 GeV and width $\Gamma_{S_{11}} = 0.184 \text{ GeV}$. The recent multi-channel analysis by Dytman *et al*[28] also suggests the existence of this resonance, although the evidence is still weak. This third S_{11} resonance, if it exists in nature, can not be accommodated by the quark model, because its mass is near the other two known S_{11} resonances, $S_{11}(1535)$ and $S_{11}(1650)$, and a quasi-bound $K\Sigma$ or $K\Lambda$ state strongly mixed with the q^3 quark state would be a likely outcome. The partial wave analysis by Deans[29] *et al* suggests that the coupling of this resonance to $K\Sigma$ would be very strong. Thus, the kaon production experiments, such as $\pi N \rightarrow KY$ and $\gamma N \rightarrow KY$, would be very important in establishing its existence. Moreover, our investigation[17] in $\gamma N \rightarrow K\Sigma$ shows that the contributions from this resonance should be further enhanced by the threshold effects. However, incorporating the contributions from this state requires more elaborate modeling and more precise data, which remains to be investigated.

Another advantage of the quark model approach for meson photoproductions is that it can be extended to the photoproductions of heavy mesons, such as the η' photoproduc-

tions. An interesting prediction[30] from the quark model emerges for the η' photoproduction; the threshold behavior of the η' photoproduction is dominated by the off-shell contributions from the s-wave resonances in the second resonance region, which can be tested in the future CEBAF experiments[31]. In Fig. 1, we show the result of our calculation for the total cross sections of the η' photoproduction off the proton target. The coupling constant $\alpha_{\eta'NN}$ is 0.35 from the fit to a few total cross section data, which is indeed consistent with the recent studies[34] suggesting it to be small. Of course, there is a large uncertainty due to the poor quality of the data. Our result does not exhibit the dominance of any particular resonance around 2 GeV region suggested by the RPI group[35]. This can be understood by the relative strength of the CGLN amplitudes \mathcal{O}_R in Eq. 5 between the s-wave resonances in the second resonance region and the resonances around 2.0 GeV in the quark model. There are two S_{11} resonances with isospin 1/2 in the second resonance region. The operator O_R in Eq. 2 for these two resonances are proportional to the quantity ξ in Eq. 5, in which the leading term does not depend on the outgoing meson momentum \mathbf{q} . On the other hand, the S or D wave resonances around 2 GeV belong to $n = 3$ in the harmonic oscillator basis. The operator \mathcal{O}_R for the $n = 3$ resonances is

$$\begin{aligned} \mathcal{O}_{n=3} = & -\frac{1}{12m_q} i\boldsymbol{\sigma} \cdot \mathbf{A}\boldsymbol{\sigma} \cdot (\boldsymbol{\epsilon} \times \mathbf{k}) \left(\frac{\mathbf{k} \cdot \mathbf{q}}{3\alpha^2} \right)^3 \\ & + \frac{1}{6} \left[\frac{\omega_{\eta'} k}{m_q} \left(1 + \frac{k}{2m_q} \right) \boldsymbol{\sigma} \cdot \boldsymbol{\epsilon} + \frac{k}{\alpha^2} \boldsymbol{\sigma} \cdot \mathbf{A}\boldsymbol{\epsilon} \cdot \mathbf{q} \right] \left(\frac{\mathbf{k} \cdot \mathbf{q}}{3\alpha^2} \right)^2 \\ & + \frac{\omega_{\eta'} k}{9\alpha^2 m_q} \boldsymbol{\sigma} \cdot \mathbf{k}\boldsymbol{\epsilon} \cdot \mathbf{q} \left(\frac{\mathbf{k} \cdot \mathbf{q}}{3\alpha^2} \right). \end{aligned} \quad (10)$$

Because the spatial wavefunctions for the S and D wave resonances are orthogonal to that of the $S_{11}(1535)$, the dependence on \mathbf{k} and \mathbf{q} of the CGLN amplitudes for the S and D wave resonances around 2 GeV should be very different from those for $S_{11}(1535)$ and $D_{13}(1520)$. Indeed, Eq. 10 shows that the amplitude for the S and D wave resonances with $n = 3$ is at least proportional to \mathbf{q}^2 comparing to the \mathbf{q} dependence of the amplitude of the $S_{11}(1535)$ in Eq. 5. Thus, the S and D wave resonances around 2 GeV give little contribution to the η' productions in the threshold region. Moreover, Eq. 10 represents the sum of every resonance with $n = 3$, and the G wave resonance has the largest amplitude among these resonances. The magnitude of the CGLN amplitudes for S and D wave resonances is even smaller than that for the $S_{11}(1535)$, since the magnitude of Eq. 10 is about 10 times smaller than that of Eq. 5. The results in Fig. 1 represents an important prediction of the quark model, since the relative strength and phases of the CGLN amplitudes for each s-channel resonance are determined by the quark model wavefunctions. It also shows the importance of the S_{11} resonances in the second resonance region in the meson photoproductions, in particular the K , η and η' productions.

In summary, the quark model approach represents a significant advance in the theory

of the meson photoproductions. It introduces the quark and gluon degrees of freedom explicitly, which is an important step towards establishing the connection between the QCD and the reaction mechanism. It highlights the dynamic roles by the s-channel resonances, in particular the roles of the S_{11} resonances in the threshold region of the K , η and η' photoproductions. Perhaps more importantly, this approach provides an unified description of the meson photoproductions. The challenge for this approach would be to go one step further so that the quantitative descriptions of meson photoproductions, in particular the polarization observables that are sensitive to the detail structure of the s-channel resonances, could be provided. This investigation is currently in progress.

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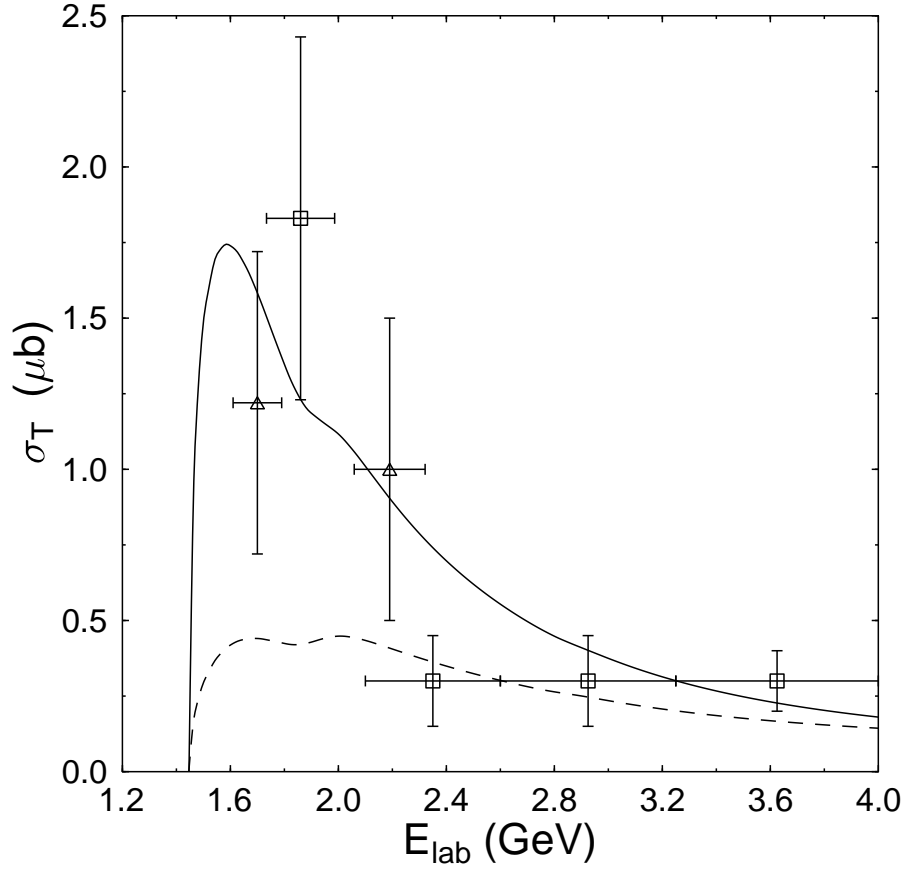


Figure 1: The total cross sections for $\gamma + p \rightarrow \eta' + p$. The difference between the solid and dashed lines represents the importance of the contribution from the resonance $S_{11}(1535)$. The experimental data are from Refs. 32 (triangle) and 33 (square).